UCLA-CEC Project: Natural Gas Pipelines and Storage Mitigation Report

Douglas Honegger
D.G. Honegger Consulting

A report on research supported by
California Energy Commission (CEC)

Report GIRS-2023-04

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1 Introduction

Prior to about 1970 the potential for earthquake-generated ground displacements was not considered for pipelines in North America. Pipelines of this vintage constitute a large fraction of the existing pipeline infrastructure. There are no regulatory requirements that impose a duty on energy pipeline operators to investigate potential seismic hazards to existing pipelines. Some energy pipeline companies have undertaken seismic hazard studies and subsequently implemented measures to retrofit their pipelines to accommodate seismic hazards. These efforts are typically driven by concerns related to potential threats to public safety, lengthy interruptions to operation in the event of earthquake damage, and financial liabilities from a large release of product.

Relevant seismic hazards for pipelines and gas storage facilities include seismic fault displacement, triggered landslides, liquefaction settlement, and lateral spread displacement. Measures that can mitigate seismic vulnerability, either fully or partially, fall into six general categories:

- Avoid the hazard
- Realign the pipeline to reduce the impact of the hazard on the pipeline
- Decrease the severity or likelihood of the hazard occurring
- Increase the pipeline strength
- Decrease the soil load on the pipeline
- Establish response measures to minimize impact of pipeline damage

These mitigation measures are equally applicable to new pipeline design or modifications for existing pipelines although implementation on existing pipelines is often far more difficult.

Selection of a particular approach is dependent upon considerations that vary with pipeline location, land-use constraints, expected failure mode, potential for collateral damage, risk acceptance philosophy, and mitigation costs. Many of the options may have limited applicability because of the type of hazard. For example, avoidance is only an option for localized ground failures such as landslides and lateral spreads. Often, there are constraints on what type of mitigation can be undertaken. Factors such as topography, constructability, right-of-way access, utility avoidance, and backfill requirements are examples of constraints that determine what mitigation measures are practicable. Urban environments are particularly restrictive with respect to the feasibility of mitigation options to improve pipeline response.

Another consideration is the desired level of performance once mitigation measures are implemented. Examples of performance goals from highest to lowest include the following:

1. No immediate interruption of normal service or required repairs
2. No immediate interruption of service and repairs can be implemented as part of normal maintenance activities
3. No immediate interruption of service but repairs need to be expedited to return to normal long-term operation
4. No immediate interruption of service but controlled shut-in of the pipeline to maintain safety and perform repairs is necessary
5. Pipeline has the potential to lose pressure integrity but no significant impact on safety, property, or the environment is acceptable; no special operational controls necessary
6. Pipeline has the potential to lose pressure integrity but significant impact on safety, property, or the minimized through operational controls

The first performance goal can generally only be achieved by rerouting the pipeline to avoid the hazard. Performance goals 2 through 4 require combinations of modifications to the pipeline alignment, hazard likelihood, pipe strength, and soil strength. Goal 5 is the classic "do nothing" approach. Goal 6 is the least desirable as it accepts the fact that there will be adverse consequences that extend beyond the pipeline operation.

The following chapters borrow heavily from guidelines prepared for the Pipeline Research Council International, Inc. (PRCI). The lead author of this report was responsible for preparing the report generated for the PRCI project. Readers are encouraged to download this free guideline document from the Pipeline and Hazardous Materials Safety Administration website at https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=202.

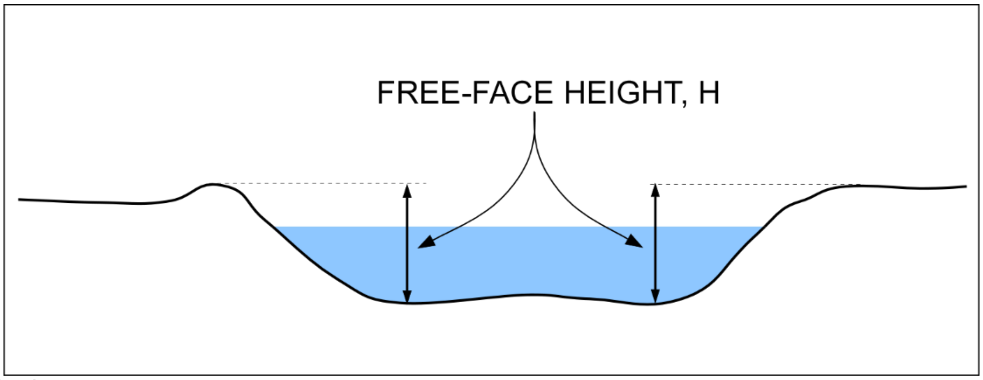
2 Hazard Avoidance

Avoiding a seismic hazard is a fool-proof means of mitigation and is best suited for individual structures or facilities. Since pipelines necessarily provide product from point A to point B, avoiding the crossing of a fault that lies between points A and B is not possible.

Landslide hazards are most commonly avoided by routing the pipelines around the bounds of the slide zone. Shallow landslides can also be avoided by deep pipeline installations that locate the pipeline in competent soils that are not prone to shear failure under intense ground shaking. This is typically accomplished by horizontal directional drilling (HDD) or other trenchless methods to avoid triggering slide movement during construction. Since the vulnerability to ground displacement increases rapidly with increasing depth of burial, knowing the possible depth of the slide plane and the length of pipeline traversing the slide zone is critical to designing an adequate mitigation concept.

Deep pipeline installations can also be a means to avoid lateral spread hazards at river crossings if the liquefaction susceptibility of the soils at the crossing decreases substantially with depth. The size of natural gas pipelines in California is conducive to long river crossing replacements using HDD or direct pipe installation methods. Short crossings can often be constructed using common cut and cover methods with river diversion. Care is needed to make sure the onshore portion of the lateral spread hazard is avoided, especially if elbows are required at the entry and exit locations to facilitate tie-ins with existing portions of the pipeline. Historically, the extent of lateral spread displacement at river crossings has generally not exceeded 200 to 300 m or more than 50 times the free-face height, the difference in elevation from the highest point on the riverbank to the deepest river depth adjacent to the bank (see Figure 1).

Figure 1. Free-Face Height Definition



Credit: DGHC

3 Modifying Pipeline Alignment

Soil surrounding a buried pipeline provides both the means by which ground displacement transfers load to the pipeline and a means by which the ground can resist the loads imposed by ground displacement. The most direct example of this is a straight pipeline exposed to ground displacement over a limited length in a direction purely parallel to the axis of the pipeline. The axial load transferred from the ground to the pipeline within the zone of ground displacement is resisted by axial soil restraint on either side of the portion of pipeline exposed to ground displacement. For simplicity, the soil loads transferred to the pipeline will be referred to as “soil restraint”.

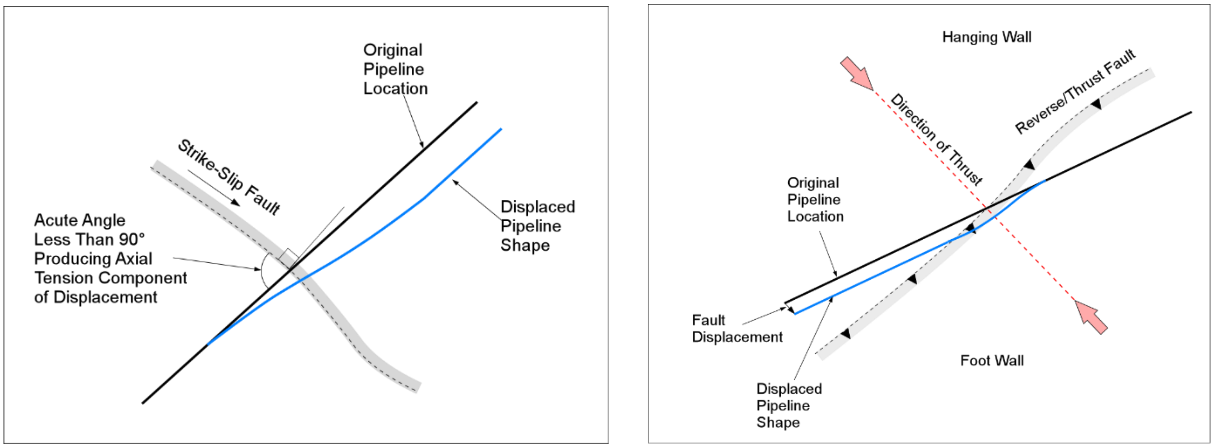
The angle of intersection of the pipeline with the zone of ground displacement is the most important factor that determines pipeline response. The objective in modifying a pipeline alignment is to achieve a favorable balance between bending strain and axial strain that will result in the maximum combined strain being less than the limits associated with tensile fracture or buckling that could result in loss of pressure integrity (i.e., partial, or complete pipeline rupture). Optimal response is achieved with an intersection angle that minimizes the direct longitudinal strain induced into the pipeline while promoting catenary tension. Catenary tension increases the effective bending strength of the pipeline, similar to a guitar string that requires more force to deflect when it is taught rather than loose. Crossing alignments that induce direct axial compression into the pipeline need to be avoided as compression could lead to upheaval buckling (Euler buckling) as illustrated in Figure 2. A direct component of axial compression will limit or prevent the development of catenary tension. The amount of lateral displacement that can be accommodated by a buried pipeline can be an order of magnitude greater if there is net axial tension instead of compression.

Figure 2. Examples of Upheaval Buckling Under Axial Compressive Loading

Credit: DGHC

For strike-slip faults, the crossing angle should be nearly perpendicular as illustrated in Figure 4, but with a slight deviation from perpendicular that will induce a small amount of direct tension into the pipeline (approximately 10° clockwise for right lateral slip or 10° counterclockwise for left lateral slip).

Figure 3. Schematics of Idealized Crossings of Strike-Slip and Reverse/Thrust Faults



a) Plan View of Buried Pipeline Crossing for Strike-Slip Fault (near perpendicular intersection)

b) Plan view of buried pipeline crossing for reverse/thrust fault (acute intersection angle).

Credit: DGHC

The crossings of reverse or thrust faults are the most difficult because there is a horizontal compressive displacement across the fault zone that must be accommodated by pipe deformation. The development of even small amounts of axial compression can greatly reduce the ability of the pipeline to withstand bending deformation from lateral soil loading. Oblique fault crossing angles, as illustrated in Figure 4 are preferred for reverse faults as perpendicular crossings induce the highest compression. The oblique orientation needs to be maintained through the fault uncertainty zone and some distance beyond. This can result in a large offset in pipeline alignment if the required pipeline heading differs greatly from the oblique crossing angle and the fault location is highly uncertain.

Normal fault crossings typically pose the least demand on pipelines because they have a horizontal tensile displacement across the fault zone. Also beneficial is the fact that the vertical uplift soil restraint is low compared to the bearing soil restraint which allows the pipeline to be pulled out of the ground. However, if the vertical component of normal fault exceeds the depth of cover to the pipeline invert, the pipeline response may no longer by displacement controlled and the amount of pipeline strain that can be considered acceptable will be greatly reduced. This type of pipeline response is often seen in shallow failures on steep slopes that have a large vertical displacement component, as shown in Figure 4. Pipeline Exposed by Pulling Up Through Soil in a Slide Zone.

Figure 4. Pipeline Exposed by Pulling Up Through Soil in a Slide Zone

Credit: DGHC

Table 1 provides a summary of recommended pipeline fault crossing alignment configurations. While pipelines can often be oriented to cross faults to have the response be tensile or minimize compressive loading, landslides and lateral spread hazards will always have both tensile and compressive response.

Table 1. Preferred Pipeline Fault Crossing Configurations

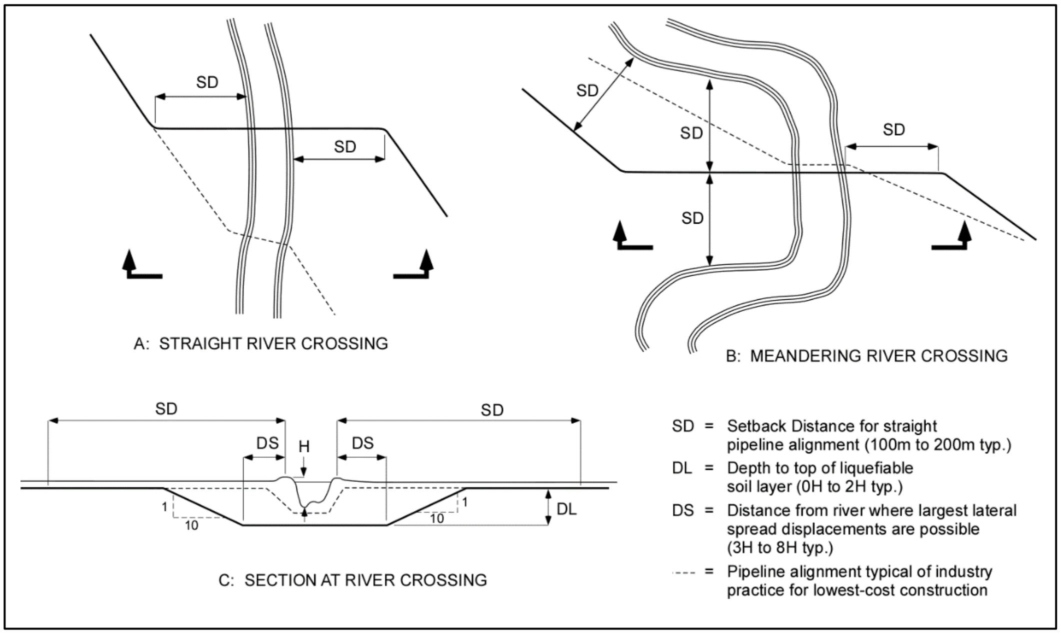
Fault Slip Style	Optimal pipeline-fault intersection angle, θ	Pipe Behavior and Strain Objective	Design Consideration
Strike-slip	Near perpendicular, ~80° to produce nominal direct tension (i.e., avoid axial compression). See example, **Error! Reference source not found.**a.	Accommodate fault rupture through localized pipe bending over short segments of approximately 5 to 10 pipe diameters plus nominal direct tension. Horizontal displacement of backfill and/or in situ soil.	Design control by tensile strain limit; wide trapezoidal trench required. Near perpendicular crossing will minimize the required length of special construction to cross the fault zone.
Normal slip	60° to 90°	Accommodate ground surface dislocation through axial elongation and uplift of pipeline through its backfill in the downthrown fault block. Perpendicular crossings will induce maximum tension into the pipeline but minimum bending. Oblique crossings will reduce direct tension but increase bending.	Significant longitudinal tension over segment of several hundred meters.
Reverse or thrust	20° to 35° See example, **Error! Reference source not found.**.b.	Accommodate fault rupture through localized pipe bending over short segment of approximately 5 to 10 pipe diameters while minimizing direct compression. Horizontal displacement of backfill and/or in situ soil.	Oblique crossing will result in a special design segment considerably longer than the fault zone width, i.e., a length indirectly proportional to sin θ.

Credit: DGHC

Pipeline alignments in which the pipeline is parallel to the direction of ground displacement is the preferred alignment for crossing landslide and lateral spread hazards. With a crossing alignment parallel to the direction of ground displacement, the pipeline response is governed by the length of pipeline in the hazard, not the amount of displacement. The reason for this is the fact that the axial soil restraint is developed after a relative displacement between the pipe and the soil far less than one inch. The axial load on the pipeline from ground displacement is resisted by tension and compression on either side of the hazard. To be effective the pipeline alignment should be nearly straight on either side of the zone of ground displacement for a distance on the same order as the length of pipeline within the hazard. For constant soil restraint conditions within and outside of the zone of ground displacement, the length of straight pipe required beyond the zone of ground displacement is half of the length of pipeline within the hazard. For the same conditions, if the axial compressive capacity of the pipeline is less than the tensile capacity, perhaps as a result of exceeding the compressive load associated with local pipe wall wrinkling, the length of straight pipe loaded in tension should be equal to the length of pipeline within the hazard. Under optimal conditions, pipelines can experience ground displacement over several hundred feet without any significant damage.

Most lateral spread hazards are associated with instability near the banks of water bodies with direction of ground displacement perpendicular to the bank. Thus, only water body crossings that are crossed by pipelines can be oriented parallel to the direction of ground displacement. For such cases, the optimum crossing is one that avoids sharp bends in profile and maintains a straight alignment beyond the influence of lateral displacement from other sources. A schematic representation of preferred pipeline alignments at river crossings subject to lateral spreading is shown in Figure 5.

Figure 5. Preferred Configurations for Pipelines Crossing Streams with Liquefiable Bank Deposits



Credit: DGHC

4 Improving Pipe Soil Interaction

The axial component of fault displacement is resisted by friction forces at the soil-pipeline interface. For a given pipeline axial force, there is a length of pipeline required to develop opposing soil frictional forces. Beyond this length, typically referred to as the “anchorage length”, the pipeline is not affected by the fault displacement and can be considered anchored. Hence, the frictional resistance provided by soil-pipeline interaction governs the length of pipeline available to accommodate axial components of ground displacement.

With very strong soil embedment, the pipeline will be highly constrained and forced to conform almost exactly to the deformation of the soil, which will give rise to increased bending strain near the location of differential ground displacement. Conversely, for relatively weak soil restraint, the pipeline will be much more capable of plowing through the soil with reduced bending curvature, possibly breaking through the ground surface. Since the objective of a good seismic design is to minimize pipe strain as a function of ground displacement, the minimization of soil restraint is fundamental to providing adequate displacement capacity.

Soil loads on buried pipelines can be reduced in several ways. The most common approach is to minimize the strength of the soils surrounding the pipeline or the frictional characteristics of the pipeline-soil interface. Potential options for implementing changes to modify the soil loading on buried pipelines are summarized below. Many of the options have limited applicability because of restrictions related to right-of-way access, the need to avoid existing subsurface structures and utilities, or the compaction requirements associated with various types of land use. Urban environments are particularly restrictive with respect to the feasibility of mitigation options to improve pipeline performance.

4.1 Minimize the Depth of Cover

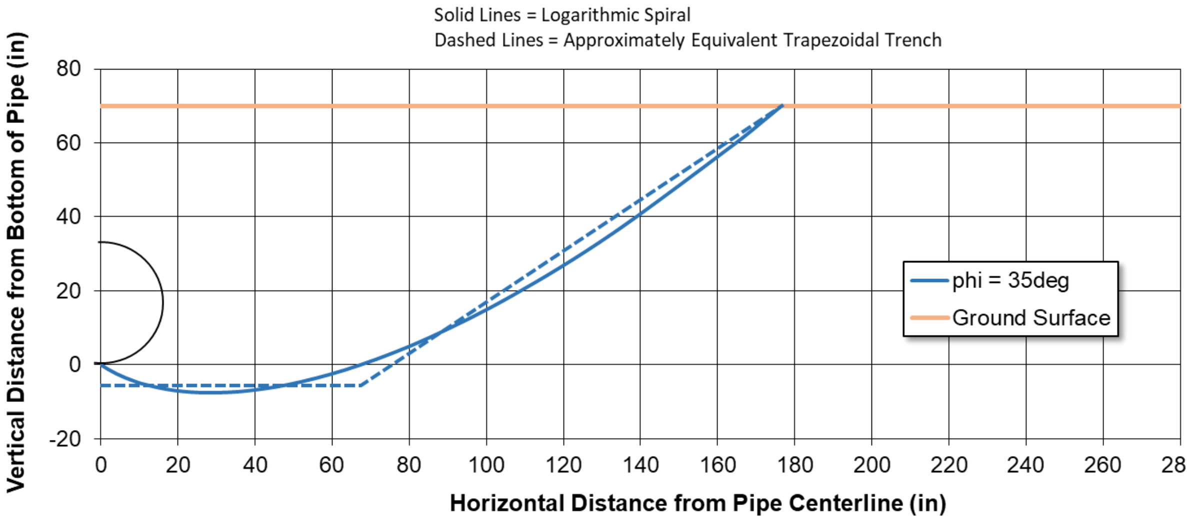
Reducing the depth of soil cover is one of the first considerations to reduce soil restraint on a buried pipeline. In locations where greater burial depth is preferred to reduce risks from surface land use (e.g., agricultural activity, roadways), supplemental barriers above the pipeline can provide the necessary protection to allow a minimum depth of cover. In normal pipeline situations, the minimum cover depth is 0.9 m except for agricultural areas where 1.2 m or greater may be required. In addition, normal pipeline depth of burial may be locally higher to accommodate topographic variations or avoid existing infrastructure. To avoid doubt during design implementation, the shallow cover at fault crossings should be specified as a *not-to-exceed value* instead of the typical practice of specifying a minimum value.

4.2 Loose Granular Backfill

A practical means for achieving minimum soil restraint is to bury the pipeline in a shallow trench filled with a loose backfill. For typical pipeline burial depths, loose granular backfills (sand or gravel) will offer less resistance to pipe movement than compacted cohesive backfill materials (clay or silty clay). A granular material with an angle of internal friction of 35° or less is recommended. The material should be obtained from a natural, rounded or subrounded fluvial deposit that is not dominated by grains of feldspar or other minerals that split along cleavage surfaces and remain angular with 100 percent of the aggregate less than one inch (25 mm) in diameter. The backfill should be placed as loosely as possible recognizing that a time-dependent increase in density is unavoidable. The most significant challenge to the use of loose cohesionless material is that the loose material may restrict the activities that can be allowed over the pipeline to avoid long-term compaction of the material.

Where native (in-situ) soil conditions are judged to have unacceptably high strength, such as soils that are cohesive, highly compacted, or lightly cemented, imported backfill material may be required. The soil replacement would need to be extended through the entire length of the fault rupture zone and some distance beyond to increase the effective anchorage length. The trench for replacement soils needs to be wide enough to envelope the bounds of the lateral bearing soil failure surface, often assumed to be a lognormal spiral. As depicted in Figure 6. Log Spiral Failure Surface, the total trench width can range from two to three times the depth to the bottom of the pipeline.

Figure 6. Log Spiral Failure Surface



Credit: DGHC

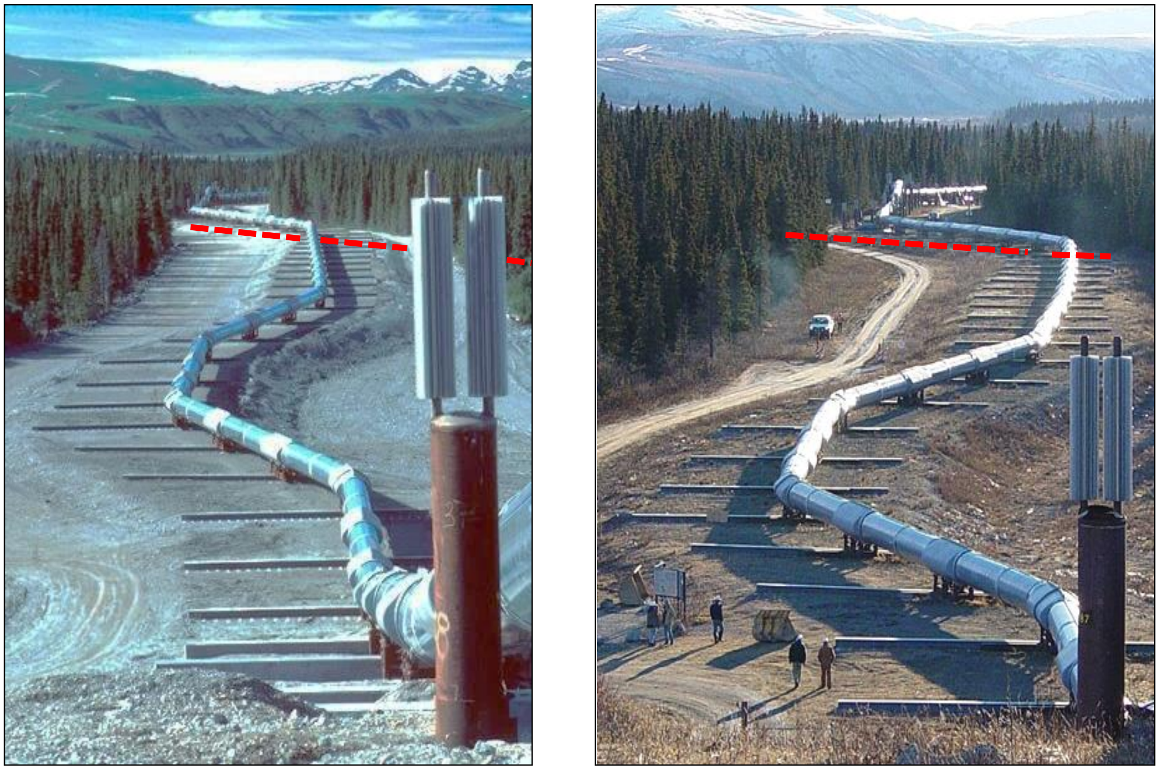
4.3 Locating Pipeline at or Above Grade

Lateral soil restraint can be greatly reduced by placing the pipeline on the ground surface or on aboveground supports. Typically, this is done by attaching sliding shoes to the pipeline that bear on structural steel members tied to the ground or mounted in an aboveground configuration (e.g., aboveground segments of the Trans-Alaska pipeline shown in

Figure 7. Before and After Pictures of Trans Alaska Pipeline at Denali Fault Rupture Location). Teflon, or other low-friction materials, can be incorporated into the construction of the sliding shoes to improve the ability of the pipeline to accommodate ground displacement by sliding laterally. Locating pipelines above ground is rarely a practical solution outside of controlled access areas or very remote regions. However, in some cases, it may be feasible to construct a sliding support configuration at the bottom of an open trench with a trench cover to protect the pipeline from vandalism and reduce the impacts on surface activities.

Placing a buried pipeline in a culvert can result in a response similar to an aboveground grade installation. The term culvert refers to any buried structure built partially or completely around the pipeline to provide an unobstructed annular space for the pipeline to deform in a direction transverse to its axial alignment. Culvert mitigation concepts require consideration of the effect of ground displacement on the culvert to assure that potential buckling or collapse of the culvert does not adversely affect the pipeline. Culvert concepts can be viewed as casings and the same problems that can arise for cased pipelines generally apply to culverts. In addition, caution is needed to assure that axial loads from thermal changes or internal pressure do not lead to buckling of the pipe within the culvert. Axial buckling can typically be prevented by incorporating bends or expansion loops in the pipeline.

Figure 7. Before and After Pictures of Trans Alaska Pipeline at Denali Fault Rupture Location



Trans-Alaska pipeline crossing of the Denali Fault, looking south before (left photo) and after (right photo) the 2002 fault rupture (location indicated by red dashed line). Right-lateral strike displacement at a 60° crossing angle was accommodated by lateral displacement of the pipeline on support beams and cold springing (bowing) of the pipe.

Credit: CEPA, 2019

4.4 Low-Friction Coating or Protective Wrapping

A smooth, hard, low-friction pipeline coating can reduce the axial soil restraint beyond what can be obtained with loose granular backfill. The use of two independent layers of geotextile wrapping has been shown to reduce the interface friction angle used to calculate maximum axial soil spring force to as low as 20° (Honegger et al., 2011[1]). An example of the installation of a

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[1] Honegger, D.G., Wijewickreme, D., Monroy, M., 2011, "Phase II Assessment of Geosynthetic Fabrics to Reduce Soil Loas on Buried Pipelines," report prepared for Pipeline Research Council International, Inc. under contract PR-268-084509, catalog No. L52325.

pipeline with dual layers of geotextile is shown in Figure 8. Use of Geotexile Wrap to Reduce Axial Soil Restraint (note dual geotextile fabric also used on trench walls to promote preferential shear plane under horizontal loading).

Figure 8. Use of Geotexile Wrap to Reduce Axial Soil Restraint

Credit: CEPA, 2019

4.5 Replacing Soil with Lightweight Materials

Replacing soil above the pipeline with lightweight material reduces axial friction force by effectively reducing overburden stresses acting normal to the pipeline. Care must be taken to maintain a proper balance between limiting pipeline restraint for ground movement, yet providing sufficient restraint to prevent upheaval buckling of straight pipe and excessive bending stress at pipe bends due to operating load conditions. Several types of materials that can be used as lightweight fill to reduce the soil restraint on buried pipelines, each with certain advantages and disadvantages.

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[1] Honegger, D.G., Wijewickreme, D., Monroy, M., 2011, "Phase II Assessment of Geosynthetic Fabrics to Reduce Soil Loas on Buried Pipelines," report prepared for Pipeline Research Council International, Inc. under contract PR-268-084509, catalog No. L52325.

Geofoam materials offer a means to reduce axial, lateral, and upward vertical soil restraint. Geofoam is a rigid cellular plastic foam of either expanded polystyrene (XPS) or extruded polystyrene (EPS). Geofoam has been used extensively in northern Europe for subgrade insulation in regions susceptible to frost heave. Another usage of geofoam in Europe and the U.S. is as low-density fill for construction over weak soils. One common application is to use geofoam as fill for bridge approaches and abutments. Geofoam varies in weight from about 160 N/m^3 ($1 lb/ft^3$) to 470 N/m3 ($3 lb/ft^3$). The compressive strength of XPS is generally less than EPS although the compressive strength of both increases with density. The typical range of compressive strengths is 140 kPa to 240 kPa (20 psi to 35 psi) for EPS and 200 kPa to 500 kPa (30 psi to 75 psi) for XPS.

Another popular lightweight fill material is foamed concrete. Foamed concrete is formed by a mixture of consists of a foaming agent, water, fly ash, and cement. The unit weight of foamed concrete can be as low as 240 N/m3 to 310 N/m3 (15 pcf to 20 pcf), with the final density dependent upon mix design, with heavier mixes employing aggregate in the mix. The primary advantage of foamed concrete is the relative ease of placement and the relatively low cost compared to geofoam.

Other lightweight materials, such as pumice or expanded shale, and cellular concrete may also be considered as a means of reducing loadings on pipelines. Although of higher density, typically 800 to 1000 N/m3 (50 to 65 lb/ft3) compared to geofoam, these materials can typically be handled and placed in the same manner as a granular fill.

A major disadvantage of lightweight backfill is that it is susceptible to flotation in areas of high water table or wash-out during periods of heavy rainfall if the trench acts as a subsurface conduit for transport of water.

5 Reducing Hazard Severity or Likelihood

Geotechnical measures can be employed to reduce the severity or likelihood of experiencing displacements related to liquefaction, lateral spreading, and triggered slope failures.

Liquefaction alone results in differential settlement along a pipeline as excess pore pressure in the liquefied soil dissipates and soil consolidation occurs. The amount of total settlement is dependent upon the total thickness of liquefiable soils beneath the pipeline and is rarely more than 3% of the total thickness. The amount of post-liquefaction settlement will vary with variations in the subsurface stratigraphy resulting in differential settlement along a pipeline traversing the zone of liquefaction. The differential post-liquefaction settlement used to assess pipeline response is typically taken as 50% to 84% of the total settlement.

The impact of liquefaction on individual structures can be mitigated by employing deep foundation support, such as piles, or various ground improvement measures such as vibrocompaction, stone columns, and dynamic densification. Such measures are typically not practicable for pipelines that may be exposed to hundreds of meters of liquefiable soil. Fortunately, energy transmission pipelines are rarely at risk in such cases as they have sufficient strength to withstand the uplift soil restraint caused by differential ground settlement.

Lateral spread displacement occurs when liquefaction causes a reduction in shear strength to the point that a slope can no longer sustain the combined driving forces from gravity and ground shaking. The most common locations for lateral spreading to occur is near the shorelines of water bodies where the water table is likely to be shallow and the soil deposits are likely to be young and relatively unconsolidated.

The most common methods to reduce the potential for liquefaction and lateral spread displacement focus on increasing the density of the soil, which reduces the likelihood of liquefaction and the degree to which soil shear strength is decreased if liquefaction occurs. The mitigation measures for lateral spread displacement are the same as for differential settlement from liquefaction and are only practicable at crossings of water bodies because of the limited area where ground improvement measures are required.

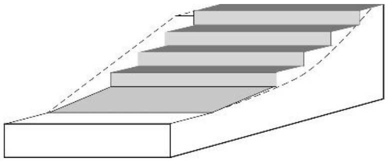
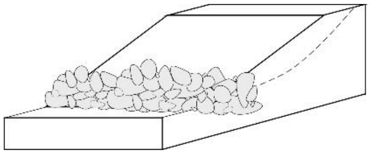
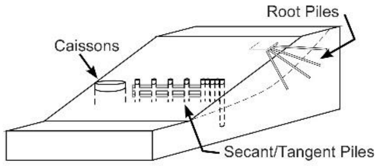
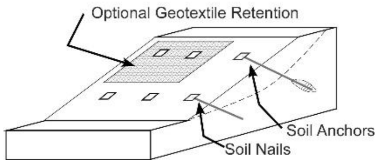
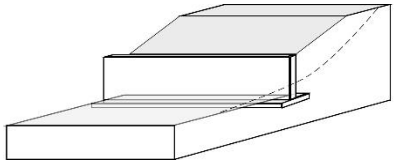
Table 2. Types of Geotechnical Slope Mitigation Methods

Mitigation Method	Limitations	Implementation Requirements
Remove Unstable Material	• May not be feasible because of right-of-way restrictions • May not be practical for large slides because of amount of material to be removed • May be difficult to implement while maintaining slide stability and pipe operation (if present) • May result in initiation of new landslide upslope • May not be feasible because of environmental restrictions	• Characterization of failure planes, soil strength, and groundwater conditions • Detailed stability analysis of conditions during and following removal of material
Bridge Unstable Area	• Feasible only for relatively small and shallow slide zones (suitable for existing pipelines)	• Characterization of failure planes and soil strength • Detailed structural analysis to assure bridge support members can withstand soil loads
Regrade Slope	• May not be feasible because of right-of-way and land use restrictions • May not be practical for large slides because of amount of material to be removed • May be difficult to implement while maintaining slide stability and pipe operation (if present) • May not be feasible because of environmental restrictions	• Characterization of failure planes, soil strength, and groundwater conditions • Detailed stability analysis of conditions during and following slope grading • Disposal of excavated soil and rock material • Assessment of impact of diverted surface water adjacent to pipeline right-of-way
Reduce Weight	• May not be feasible because of right-of-way restrictions • May not be practical for large slides because of amount of material to be replaced • May be difficult to implement while maintaining slide stability and pipe operation (if present) May not be feasible because of environmental restrictions	• Characterization of failure planes, soil strength, and groundwater conditions • Detailed stability analysis of conditions during and following replacement of material
Reduce Surface Water Infiltration Reduce Groundwater Level	• May not be feasible because of the volume of water to be rerouted or removed and areas available for water discharge • Environmental restrictions may prevent discharge of drained subsurface water	• Characterization of failure planes, soil strength, and groundwater conditions • Estimates of surface water deposited by precipitation events and local drainage patterns • Detailed stability analysis of conditions before and after groundwater control measures • Assessment of impact of diverted surface water on adjacent to pipeline right-of-way • Monitoring and maintenance of drainage diversion mechanism • Assessment of groundwater level lowering on local wells
Buttresses, Counterweight Fill, and Toe Berms	• May not be feasible because of right-of-way and land use restrictions • May not be effective for deep-seated slides • Must be founded on firm foundation • May not be feasible because of environmental restrictions	• Characterization of failure planes, soil strength, and ground water conditions • Detailed stability analysis of conditions prior to and following construction • Estimates of surface water deposited by precipitation events and local drainage patterns

Structural Retaining Systems	• Rigid systems may not be able to withstand deformations • May not be able to be installed below sliding surface • Suitable for small slides only	• Characterization of failure planes, soil strength, and ground water conditions • Detailed stability analysis of conditions prior to and following construction • Estimates of surface water deposited by precipitation events and local drainage patterns
Anchors	• Foundation materials may not have sufficient strength to support anchor tension necessary to carry shear loads from sliding soil mass	• Characterization of failure planes, soil strength, and groundwater conditions • Detailed stability analysis of conditions prior to and following construction • Estimates of surface water deposited by precipitation events and local drainage patterns
In situ Soil Reinforcement	• Most effective for dense granular and stiff silty clay slopes • Long term integrity of reinforcement (soil nails, soil anchors, and piles) needs to be assured in permanent installations	• Characterization of failure planes, soil strength, and groundwater conditions • Detailed stability analysis of conditions prior to and following construction • Estimates of surface water deposited by precipitation events and local drainage patterns
Bank Armor	• Useful only at locations experiencing soil erosion from water flow leading to slope instability • Does not add to overall stability (unless armor mass is significant), only decreases soil loss rate	• Characterization of watercourse peak flows and direction • Characterization of soil loss and impact on slope stability • Impact of armoring on downstream areas (may increase bank or bed erosion at other locations)
Watercourse Flow Re-Direction	• May not be feasible because of land use and environmental restrictions • Useful only at locations experiencing soil erosion from water flow leading to slope instability • Does not add to overall stability, only decreases soil loss rate	• Characterization of watercourse peak flows and direction • Characterization of soil loss and impact on slope stability • Impact of flow re-direction on upstream and downstream areas (may increase bank or bed erosion at other locations)

Credit: PRCI 2009

Table 3. Evaluation of Different Geotechnical Slope Improvement Methods

Method	Mechanism	Advantages	Disadvantages
Regrade Slope 	Reduce driving forces	Can be carried out using conventional earth moving equipment. Can be combined with construction of toe berm/buttress. Can provide access for other measures such as slope reinforcement, installation of drainage measures	Detailed knowledge of subsurface conditions and critical failure plane required. May require excavation and disposal of large volumes of material. Not generally suitable for deep seated landslides or long slopes above pipelines. Requires care to prevent instability during regrading May require significant regulatory approvals, agreements with neighboring property owners and extensive revegetation and landscaping/environmental mitigation.
Toe Berm/Buttress 	Increase stability at toe	Can be carried out using conventional earth moving equipment. Can be combined with regrading	Detailed knowledge of subsurface conditions and critical failure plane required. May require excavation and placement of large volumes of material. May require significant regulatory approvals, agreements with neighboring property owners and extensive revegetation and landscaping/environmental mitigation.
Slope Reinforcement   	Increase shear resistance along slide plane	Can be used to provide improved shear resistance along one or more slide planes, and at various depths not treatable using slope regrading and toe berm methods	Detailed knowledge of subsurface conditions, critical failure plane, as well as expected direction of landslide movement required. Slope reinforcement typically requires the use of specialty contractors. Installation of slope reinforcement above or below pipeline alignment may result in disturbance of slope and increased landslide risk during installation, as well as significant regulatory approvals, agreements with neighboring property owners and extensive revegetation and landscaping/environmental mitigation.
Retaining Structure 	Provide external resisting force	Can permit development of effective toe buttress support within restricted pipeline corridors Can be combined with regrading	Detailed knowledge of subsurface conditions and critical failure plane required. May require use of specialty contractors. Not generally suitable for deep seated landslides since foundation of retaining structure must be located below or outside failure plane. Requires care to prevent instability during excavation for foundation construction at toe of slide May require significant regulatory approvals, agreements with neighboring property owners

Credit: PRCI 2009

6 Reducing Impact of Pipeline Damage

Operational mitigation measures come into play when other measures to avoid or reduce the hazard are not feasible. Operational mitigation can generally be categorized as passive or active based upon whether or not the measures require reaction to changing conditions (active) or reaction after an event has occurred. Active measures may include such items as periodic strain relief. Passive measures typically aim to limit the impact of pipeline failure. Examples of passive operation mitigation measures include the following:

1. Increasing stand-off distance through additional land procurement and access control measures
2. Constructing protective barriers to minimize thermal exposure in the event of gas ignition
3. Installing line-break valves to limit loss of pipeline contents and duration of hazardous conditions in the event of pipeline damage
4. Pre-positioning materials and equipment to facilitate rapid repair to minimize duration of a hazardous service outage

Active measures require some type of monitoring focused on pipeline movement, ground movement, and changes in the vicinity of the pipeline such as large rainfall events, land use change changes. These can be employed singly or together. Monitoring provides information that determines what actions are needed and how rapidly those action need to be implemented. There are three components that are common for active operational mitigation measures:

1. Develop and implement a monitoring plan that provides the desired resolution in understanding pipeline vulnerability and can generate information within a time interval to allow response actions to be carried out.
2. Establish monitoring result trigger points for specific response measures.
3. Provide the means and methods to effectively implement response measures. These measures should be explicitly defined operations manuals or emergency response plans. In addition to planning, there may be a need to pre-position materials and equipment and establish on-demand contractual relationships with essential contractors and service providers.

The methods and levels of active monitoring necessary to support active operational mitigation are highly variable and will depend upon an assessment of the relative likelihood and severity of ground displacement on a case-by-case basis. Factors that influence decisions on monitoring programs include the following:

1. Potential for significant injury or death or damage to property or the environment.

2. The level of knowledge regarding the potential for earthquake-generated ground displacement.
3. The amount of warning time needed to implement mitigation measures.

The most significant challenge in assessing the effectiveness of monitoring and implementing an active operational mitigation measure is assigning the probability of successfully responding to adverse ground displacements before significant pipeline or environmental damage has occurred. This is particularly true for pipelines located in remote regions or regions where year-round access may be limited by weather or ground conditions. These factors are exacerbated in a post-earthquake environment increased demand for contractor services, restricted accessibility from transportation system damage, disruption of services such as fuel, commercial transactions, and lack of hotel accommodations because of damage to electrical, water, and sewer systems. The uncertainty in the effectiveness of active operational mitigation measures can be offset in some cases by having a high degree of certainty in the knowledge of the level (length and depth) of ground displacement that can occur before the pipeline does sustain significant damage. If the ‘worst case’ movement cannot significantly damage the pipe, then there is less urgency in an intervention occurring in a timely manner.

The option also exists to “pre-implement” a pipeline design measure to increase the level of ground displacement that the pipeline can withstand prior to sustaining damage. This increases the likelihood that the adverse condition will be identified and corrected. This does require a monetary investment which needs to be offset against the potential benefits of reduced risk.

7 Mitigation Measures for Gas Storage Fields

Gas storage fields in California are extremely variable in terms of size and vintage. The types of mitigation measures available for gas storage fields can be separated into three main components:

1. The well and well head assembly
2. Small diameter pipelines connecting the wells to the processing facility and larger pipelines transmitting gas to and from the storage field
3. The processing facility where gas in compressed for injection and cleaned for withdrawal

The only earthquake threat to the actual gas well is fault displacement at depth. There is no means to mitigate the damage caused by fault displacement but measures can be taken to seal the upper sections of the well to prevent stored gas from escaping.

The primary threat to the well head and connected piping is from earthquake triggered ground displacement. The mitigation measures for this hazard are the same as summarized in Chapter 5.0.

The processing facility generally contains equipment components similar to a small oil refinery without tank storage. The potential for damage to structures and non-structural components is largely related to the severity of ground shaking at the facility. The level of shaking that a facility can withstand before damage occurs is based upon the level of seismic design or retrofit measures that have been undertaken. There are several guidance documents detailing approaches for the seismic evaluation of the petrochemical facilities that are applicable to storage field processing facilities:

- ASCE, 2020, “Guidelines Seismic Evaluation and Design of Petrochemical Facilities,” ASCE 48266.

- ASCE, 2017,”Seismic Evaluation and Retrofit of Existing Buildings,” ASCE/SEI 41-17.

- CalARP Program Seismic Guidance Committee, 2019, “Guidance for California Accidental Release Prevention (CalARP) Program Seismic Assessments,” prepared for Region 1 Local Emergency Planning Committee, January [https://emd.saccounty.gov/EC/HM/Documents/SGD%20LEPC%20I%20Approved%2008%2007%202019.pdf].

- FEMA, 2005, “Earthquake Hazard Mitigation for Nonstructural Elements,” FEMA 74-FM, September, { https://mitigation.eeri.org/files/FEMA74_FieldManual.pdf].

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PRCI, 2009, “Guidelines for Constructing Natural Gas and Liquid Hydrocarbon Pipelines in Areas Subject to Landslide and Subsidence Hazards,” report prepared by D.G. Honegger Consulting, C-CORE, and SSD, Inc., Catalog No. L52292, https://primis.phmsa.dot.gov/matrix/FilGet.rdm?fil=4507&s=CF95F28385C34AEE86AE1E71EEE36DBB&c=1 [last accessed February 21, 2023].